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## Modeling, Characterization and Analysis of the dynamic behavior of heat transfers through polyethylene and glass walls of Greenhouses

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### Abstract

*The conventional agricultural tunnel greenhouse is highly widespread in Mediterranean countries, despite the shortcomings it presents, specifically the overheating during the day and the intense cooling at night. This can sometimes lead to an internal thermal inversion. The chapel-shaped glass greenhouse is relatively more efficient, but its evolution remains slow because of its investment cost and amortization.*

*The objectives of the agricultural greenhouse are to create a microclimate that is favorable to the requirements and growth of plants from the surrounding climatic conditions and produce cheap off-season fruits, vegetables and flowers which must be highly available all along the year. The agricultural greenhouse is defined by its structural and functional architecture as well as by the optical, thermal and mechanical qualities of its wall and the accompanying technical support.*

*The greenhouse is supposed to be a confined environment where there is an exchange of several components. The main intervening factors are: light, temperature and relative humidity.*

*When protected, the culture heats up more than when in free air because of the wall that acts as a barrier to harmful influences of the wind and the surrounding climatic variations as well as to the reduction in internal air convection.*

*This thermal evolution state depends on the air-tightness degree of the cover and its physical characteristics. It has to be transparent to solar rays, and must as well absorb and reflect infrared rays emitted by the soil. This leads to trapped solar rays, called the "greenhouse effect". In this article, we propose the dynamic modeling of the greenhouse system, the characterization and analysis of the thermal behavior of the wall for both experimental greenhouses, where the first one is made of polyethylene (tunnel greenhouse) and the second of glass (chapel-shaped greenhouse), throughout experimentation and simulation which finally lead to identifying the evolution in the thermal loss coefficient (K) through the wall.*

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**Keywords:** Greenhouse, Microclimate, Thermal, Materials, Modeling, Micrometeorology, Agro-system management, Solar energy, Energy saving.

### 1. Introduction

*Initially, the greenhouse is a simple enclosure limited by a transparent wall. This is the case of conventional Tunnel and Chapel-shaped Greenhouses which are widely used in the Mediterranean Basin. They amplify certain characteristics of the surrounding climate and are characterized by internal energy variations and cause some quite significant heat losses due to the low inertia of the system. In order to maintain a microclimate that fulfills the requirements of the protected culture, an energy intake is needed to heat the enclosure, specifically by night. In the present study, we deal with the global heat losses that occur inside the greenhouse system. Thermal losses, through leakage due to the quality of air-tightness of the greenhouse system and those due to latent heat fluxes that are extracted by ventilation, are studied on the basis of research works and articles previously published. In this work, we focus on thermal losses through the wall of the two experimental greenhouses, one is tunnel-shaped and made of polyethylene and the second is chapel-shaped and made of glass. This is especially to characterize the dynamic operation of the complex greenhouse system with its various components (soil, cover, culture, internal and external environments), develop models that allow reproducing the basic properties, mechanisms and interactions between the different components and make a quantitative and qualitative analysis of the thermal behavior of the agricultural greenhouse wall, by identifying the essential parameters of the system, characterizing and analyzing the evolution of the overall thermal loss coefficient (K) through the wall.*

## Nomenclature :

Al and C: parameters of the <i>greenhouse air renewal model</i> (.)(.)	$Q_p$ : heat flow through the greenhouse wall ( $\text{wm}^{-2}$ ).
$C_{ai}$ : <i>heat capacity of soil</i> inside the greenhouse ( $\text{KJm}^{-2}\text{K}^{-1}$ )	$R_g$ : outside global radiation ( $\text{wm}^{-2}$ ).
$d_f$ : leakage rate ( $\text{m}^3\text{s}^{-1}$ )	$S_f$ : leak area ( $\text{m}^2$ )
e: material thickness (m)	$T_{ai}, T_{ae}$ : dry temperature of air inside and outside, respectively (K)
$h_{si}$ : convective exchange coefficient (air/soil) ( $\text{w/m}^2\text{K}$ )	$T_{pi}, T_{pe}$ : temperatures of internal and external faces of the greenhouse wall (K)
$h_{pi}, h_{pe}$ : superficial exchange coefficients at internal and external walls	$T_{si}, T_{se}$ : soil temperatures inside and outside, respectively (K)
K: <i>overall heat transfer coefficient</i> through the greenhouse wall ( $\text{wm}^{-2}\text{K}^{-1}$ )	$\tau$ : <i>thermal time-constant of the system</i> (s)
$K_l$ : transfer coefficient of latent heat by ventilation ( $\text{wm}^{-2}\text{hPa}^{-1}$ ).	$\tau_{ir}$ : <i>infra-red transmission factor</i> (.)
$K_s$ : transfer coefficient of sensible heat by ventilation ( $\text{wm}^{-2}\text{K}^{-1}$ )	v: <i>wind speed</i> ( $\text{m.s}^{-1}$ )
$P_{ai}, P_{ae}$ : partial pressures of water vapor of internal and external air ( $\text{hPa}$ )	V: <i>volume</i> ( $\text{m}^3$ )
$Q_{air}, Q_{sol}$ : amount of heat brought by the heating system to internal air and internal soil ( $\text{wm}^{-2}$ ).	$\alpha$ : absorption rate of external global radiation by greenhouse air (.)
$Q_c$ : convective losses from greenhouse ( $\text{wm}^{-2}$ ).	$\beta$ : absorption rate of external global radiation by inside soil (.)
	$\lambda$ : coefficient of thermal conductivity ( $\text{wm}^{-1}\text{K}^{-1}$ )
	ST: Tunnel greenhouse
	SC: Chapel-Shaped greenhouse

## 2. Presentation of the two experimental greenhouses

### 2-1. The Tunnel greenhouse

The experimental tunnel greenhouse occupies a floor area equal to  $320\text{m}^2$ ; 8 m wide, 40 m long and 4 m high. The entire structure is made of lightweight galvanized metal tubes. The cover is a simple polyethylene wall,  $15.10^{-5}$  m thick. The access door is 2.40 m wide and 2.50 m high, easily manipulable and airtight enough. The inside soil is totally isolated from the outside, by means of a 0.70 m thick veil made of building stones and concrete.

### 2-2. The chapel-shaped greenhouse

The experimental Chapel-shaped greenhouse occupies a floor area equal to  $210\text{m}^2$ , 7 m wide; 30 m long and 4 m high at the center. The structure is all metal with minimal shading. The greenhouse is entirely covered with a 3 mm thick glass wall. The sliding access doors are relatively airtight. Similarly, the inside soil is totally isolated from the outside by means of a 0.80 m thick veil made of building stones and concrete.

### 2-3. Equipment and experimental facilities

Air renewal or ventilation is carried out by two extractors placed on both sides of the greenhouse. The heating system includes:

- An under-floor heating by means of PVC serpentine pipes, placed at a depth of 0.40 m under the ground.
- An air heating provided by two heaters located on the axis of the greenhouse at a height of 3m.

Irrigation and fertilization are performed simultaneously through a drip system managed by an Automatic Fertigation System.

Control equipments include electrical cabinets that centralize all measurements. The control system of the greenhouse climate data is provided by the system AGAPES (An algorithm for Automatic Control of Productions inside Greenhouses). This system includes an acquisition and control module (MAC) that ensures the acquisition of measurements and the commands of devices connected to the computer that serves as a supervisor. It allows to:

- Display controllable and non-controllable climate measurements
- Modify climate instructions
- Constitute a data base
- Scan measurements every minute, establish the average values of all sensors every fifteen minutes and keep them into memory.

The sensors used for measuring dry and wet temperatures of indoor and outdoor air, are ventilated psychrometers using electrical resistance probes (copper probes).

Wall temperatures were measured on each greenhouse by means of very fine copper-constantan thermocouples (0.1mm wire diameter) placed on the wall, outside ( $T_{pe1}$  and  $T_{pe2}$ ) and inside ( $T_{pi3}$ ,  $T_{pi4}$  and  $T_{pi5}$ ).

The atmospheric radiation was measured using a pyrgeometer (Eppley).

The wind speed was measured using a cup anemometer (starting threshold  $\pm 0.5$  m/s) placed at a height of 4 m near the two greenhouses.

Temperature measurements of wet and dry air as well as wall temperatures (at night) were done with a 0.02K resolution, including the 0.1 K errors in the acquisition chain. When one of these differences is  $\leq 0.1\text{K}$ , we consider that there is condensation.

This measurement and all subsequent measurements in the nighttime are then discarded.

After selecting the measurements and counting the average values, estimated over 15 minutes time steps, data and measurements processing starts.

## 3. Specificity of the greenhouse heating compared to that of residential buildings

The greenhouse exhibits a quite different thermal behavior compared to residential buildings, because of its particular characteristics:

- A lightweight structure supporting a low inertia transparent envelope which transmits a large amount of solar radiation
- A culture that captures the bulk of this radiation and converts it mainly into latent heat of vaporization (plant transpiration) and into sensible heat: it hence participates in the exchange of energy and mass.
- A floor that absorbs the incident radiation and converts some of it into latent heat. Soil is the essence of the thermal mass of the greenhouse, unlike buildings where the walls and roof are the predominant features of storage.

The greenhouse is characterized by a heat transfer phenomena through radiation, conduction-convection and leakage.

#### 4. Concept of the system approach

The system model can be defined by the mathematical relationship  $\xi$  between inputs E and outputs Y of the system.

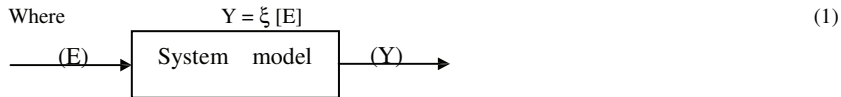


Fig. 1. Diagram and model of a

#### 4-1. Mathematical expression of the greenhouse system

The general equations for the greenhouse system that we intend to study and for which we make some simplifications are as follows:

Equation of State describing the internal behavior of the greenhouse system.

$$\frac{dX_{(t)}}{dt} = AX_{(t)} + BE_{(t)} \quad (2)$$

The output equation is :

$$Y_{(t)} = CX_{(t)} + DE_{(t)} \quad (3)$$

Coefficients A, B, C and D are matrices whose dimensions are related to the respective dimensions of *state vectors*, control, disturbance and output.

Where:

A: the dynamic matrix system, of dimension (n x n)

B and D: matrices that characterize the control parameters of the system, of dimension (q x n)

C: the matrix of observations, of dimension (q x n).

#### 4-2. Simulation

A simulation sequence usually involves two steps. In the first step, we try to make a description of the network to be studied and then edit the tasks and commands to execute. In the second step, the executed commands lead to the actual treatment of the results.

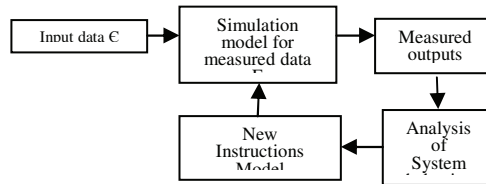


Fig.2. Simulation diagram

### 5. Physical modeling of greenhouses and the choice of a simplified model

Establishing the general equations governing the greenhouse crop, system under dynamic condition, and choosing a quite realistic simplified model can contribute to the analysis of the behavior of the whole "greenhouse-crop" system

#### 5-1. Basic principle

The physical study of the greenhouse covers all physical processes involved in its operation. It is therefore a prerequisite for developing a mathematical model.

Energy balances represent the evolution rules of the model from an initial state to a final state. They reflect the principle of energy conservation. The *energy balance equation* in its general form is written as:

The right hand side of the equation is a differential term with respect to time. It characterizes the inertia of the element and reflects the ability of the state variable to evolve rapidly (low inertia) or slowly (high inertia) under the action of external stresses.

#### 5-2. Greenhouse model

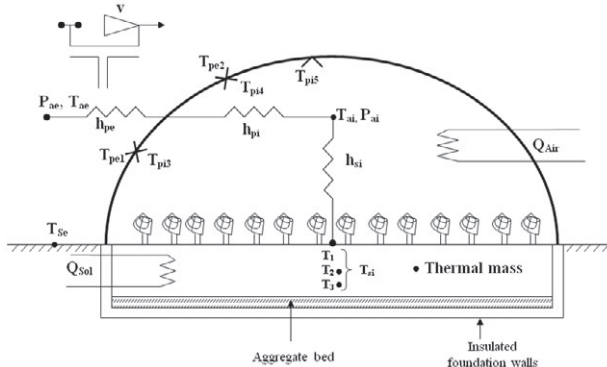


Fig.3. Reduced model

### 5-3. R.C greenhouse model of first order

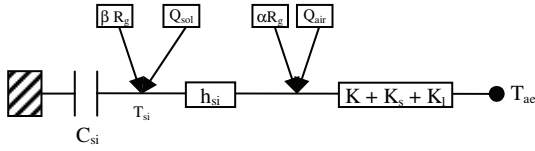


Fig.4.. R. C greenhouse model of energy balance

### 5-4. Energy balance

#### 5-4-1. Energy balance of internal atmosphere

$$\alpha R_g + Q_{air} + h_{si}(T_{si} - T_{ai}) + K(T_{ae} - T_{ai}) + K_{si}(T_{ae} - T_{ai}) + K_l(p_{ae} - p_{ai}) = 0 \quad (4)$$

#### 5-4-2. Assessment of water vapor in greenhouse air

$$C_l \frac{dp_{ai}}{dt} = T_r - K_l(p_{ai} - p_{ae}) + \phi_l \quad (w.m^{-2}) \quad (5)$$

In micro meteorology, the energy balance equation often uses the Bowen ratio ( $B_0$ ) which represents the ratio of sensible heat flux to latent heat flux, that is:

$$B_0 = \frac{K_s(T_{ai} - T_{ae})}{K_l(p_{ai} - p_{ae})} \quad (6)$$

The energy balance equation (4) of the *internal greenhouse atmosphere* becomes:

$$\alpha R_g + Q_{air} - h_{si}(T_{ai} - T_{si}) - K(T_{ai} - T_{ae}) - K_{si}(T_{ai} - T_{ae}) \left[ \frac{(B_0 + 1)}{B_0} \right] = 0 \quad (7)$$

#### 5-4-3. Energy balance of thermal mass

$$C_{si} \frac{dT_{si}}{dt} = h_{si}(T_{ai} - T_{ae}) + Q_{sol} + \beta R_g \quad (8)$$

The energy balance of thermal mass can be formulated as a function of all parameters and flows involved in the greenhouse environment, by the expression:

$$C_{si} \frac{dT_{si}}{dt} = (\alpha + \beta)R_g + Q_{sol} + Q_{air} - K(T_{ai} - T_{ae}) - K_s(T_{ai} - T_{ae}) \left[ \frac{(B_0 + 1)}{B_0} \right] \quad (9)$$

### 5-5. Overall heat transfer coefficient through the greenhouse wall

Heat losses through the wall reflect the efficiency level of the material covering the greenhouse. It acts as a barrier between the microclimate and its surroundings. *Energy compensation to heat the inside of the greenhouse, as a result of these energy losses, is a significant energy complement.*

The evaluation of the flow of heat exchanged between the inside and the outside of the greenhouse through the wall is closely related to the overall coefficient ( $K$ ) of heat transfer through the wall of the greenhouse. Its rational approach represents an important tool to decide on the choice of material types of the envelope as well as for other technical applications, specially the architectural and structural orientation of greenhouses.

The flux  $Q_p$  of heat exchanged between the inside and the outside of the greenhouse, can be deduced from equation (7) of the energy balance of the greenhouse internal atmosphere. It is expressed by the equation:

$$Q_p = K(T_{ai} - T_{ae}) \quad \text{in } (w/m^2) \quad (10)$$

The model for estimating the overall coefficient ( $K$ ) of heat transfer through the wall is defined as follows:

*In steady and continuous night operation*, heat transfer expressions through the wall are:

In a continuous night operation, heat flow expressions through the wall are:

On the inside face of the wall:

$$Q_p = h_{ri}(T_{ai} - T_{pi}) + h_{ci}(T_{ai} - T_{pi}) = h_{pi}(T_{ai} - T_{pi}) \quad \text{in } (w/m^2) \quad (11)$$

Through the wall:

$$Q_p = \frac{\lambda}{e}(T_{pi} - T_{pe}) \quad \text{in } (w/m^2) \quad (12)$$

On the outside face of the wall:

$$Q_p = h_{re}(T_{pe} - T_{ae}) + h_{ce}(T_{pe} - T_{ae}) = h_{pe}(T_{pe} - T_{ae}) \quad \text{in } (w/m^2) \quad (13)$$

From equation (12)

$$\frac{Q_p}{K} = \frac{Q_p}{h_{pi}} + \frac{Q_p}{h_{pe}} + \frac{Q_p}{\lambda/e} \quad (K); \text{ Therefore: } \frac{1}{K} = \frac{1}{h_{pi}} + \frac{1}{h_{pe}} + \frac{1}{\lambda/e} \quad (14)$$

The overall coefficient of heat transfer through the greenhouse wall will be:

$$K = \frac{h_{pi} h_{pe} \lambda}{\lambda(h_{pi} + h_{pe}) + e h_{pi} h_{pe}} \text{ in } (w/m^2K) \quad (15)$$

### 5-6. Formulation and integration of the reduced model

After integrating equations (7) and (8) and putting them into a recurring form, between time steps  $n$  and  $n + 1$ , a numerical approximation gives, after simplification of the Bowen ratio,  $B_0 = f(T_{ai}, P_{ai})$ :

$$T_{si(n+1)} = T_{si(n)} \exp\left(-\frac{\Delta t}{\tau}\right) + \left(1 - \exp\left(-\frac{\Delta t}{\tau}\right)\right) \left(1 \frac{\alpha h_{si} + \beta \mu}{h_{si}(K + K_s)} \frac{\mu}{h_{si}(K + K_s)}\right) \begin{pmatrix} T_{ae} \\ R_g \\ Q_{Sol} \\ Q_{air} \end{pmatrix} \quad (16)$$

$$T_{ai(n+1)} = \frac{h_{si}}{h_{si} + K + K_s} T_{si(n+1)} + T_{ai(n+1)} = \frac{h_{si}}{h_{si} + K + K_s} T_{si(n+1)} + \left(\frac{K + K_s}{h_{si} + K + K_s} \frac{\alpha}{h_{si} + K + K_s} \frac{1}{h_{si} + K + K_s}\right) \begin{pmatrix} T_{ae} \\ R_g \\ Q_{air} \end{pmatrix} \quad (17)$$

where  $\tau$  is the time constant of the system and  $\mu$  an intermediate parameter defined by:

$$\tau = \frac{C_{si} \mu}{h_{si}(K + K_s)} \text{ and } \mu = h_{si} + K + K_s \left(\frac{(B_0 + 1)}{B_0}\right)$$

From the solution of the system of equations (7) and (17), one can see that the greenhouse behaves as a thermal system of order 1. Furthermore, it allows predicting temperatures of the internal atmosphere ( $T_{ai}$ ) in dynamic operation when the system solicitations and commands are known.

### 6. Results

The issue of management and control of the greenhouse system, where physical and biological subsystems coexist and are all subject to actions and solicitations from the surrounding climate, requires the development of theoretical bases of modeling and system control and, consequently, means choosing the appropriate model.

Sequences of 5 days per month	Green-house	$T_{sio}$ (K)	$C_{si}$ (KJm <sup>-2</sup> K <sup>-1</sup> )	$h_{si}$ (wm <sup>-2</sup> K <sup>-1</sup> )	$\alpha$ (.)	$K$ (wm <sup>-2</sup> K <sup>-1</sup> )	$\tau$ (h)	$\epsilon$ (°C)
JANUARY	S.T	288	1740 ± 1470	12,7 ± 2,4	0,41±0,07	10,2 ± 2,2	95,7	2,31
	S.C	288	1417 ± 1340	11,4 ± 1,4	0,37±0,03	7,2 ± 1,5	75,5	1,77
MARCH	S.T	289	794 ± 317	16,1 ± 4,2	0,30±0,02	12,4 ± 3,6	41,7	1,71
	S.C	289	701 ± 247	13,2 ± 3,1	0,35±0,02	6,2 ± 0,4	21,2	1,34
APRIL	S.T	291	320 ± 247	14,7 ± 2	0,35±0,07	12,2 ± 4,2	14,1	1,49
	S.C	291	295 ± 114	12,4 ± 1,4	0,32±0,05	7,4 ± 1,7	11,5	1,17
MAY	S.T	293	124 ± 74	11,7 ± 1,9	0,42±0,04	11 ± 3	12,4	0,57
	S.C	293	117 ± 24	10,7 ± 1,3	0,4±0,09	6,1 ± 0,5	10,5	0,45

Table..1. Values recorded for tunnel (ST) and Chapel-shaped (HC) greenhouses of parameters  $T_{sio}$ ,  $C_{si}$ ,  $h_{si}$ ,  $\alpha$ ,  $K$ , and  $\tau$  with the *minimization criterion*  $\epsilon = \sqrt{J/N}$ . The fixed parameters are:  $AL\sqrt{C} = 0.26$ ,  $\beta = 0.2$ ,  $sf = 0.9$  m<sup>2</sup> and  $df = 0.8$  m/s for ST and  $sf = 0.5$  m<sup>2</sup> and  $df = 0.4$  m<sup>3</sup>/s for SC.

The results in table 01, found from the identification of parameters in the energy balance equation, using the Bowen ratio (Eq. 6, 16 and 17), show that the criteria obtained tend to improve and seem relatively viable, depending on whether the initial temperature  $T_{sio}$  is fixed or not. These results vary from 0.45 to 1.77 °C for the chapel-shaped greenhouse and from 0.57 to 2.31 °C for the tunnel greenhouse. These values are relatively small compared to the 0.5°C precision in the series of temperature measurements, except for the January sequence where the  $C_{si}$  value is not realistic and is markedly different from the values in other sequences.

$C_{si}$ : *heat capacity values of soil*. It varies from 117 to 1417 KJm<sup>-2</sup> K<sup>-1</sup> for SC and from 124 to 1740 KJm<sup>-2</sup> K<sup>-1</sup> for ST. The January sequence remains outsized.

$h_{si}$ : the coefficient values of convective exchanges between air and soil inside the greenhouse seem slightly higher.

$\alpha$ : the absorption rate values of the *global external radiation* by air and vegetation inside remain coherent and consistent with reality.

$K$ : the overall coefficient values, of heat transfer through the wall, range from 6.1 to 7.4 Wm<sup>-2</sup>K<sup>-1</sup> for SC and from 10.2 to 12.4 Wm<sup>-2</sup>K<sup>-1</sup> for ST. The variation of this coefficient (K) which is from ± 0.5 to ± 1.5 for SC and from ± 2.2 to ± 4.2 for ST are acceptable and the values of (K) remain consistent, especially at night.

$\tau$ : The time constant  $\tau$  of the system ranges from 10.5 to 75.5 hours for SC and from 12.4 to 95.7 hours for ST. The improvement on this parameter was significant, except for the January sequence.

The differences in the measured temperatures ( $T_{af} - T_{pe}$ ) tend to increase as the wind speed goes from 0 m/s to 10 m/s. They vary between 0.2 and 0.7 °C for SC and are less than 0.12 °C for ST. Temperatures  $T_{pi}$  and  $T_{pe}$  measured on the wall in PE of the ST are extremely close, given the inertia of the material. The differences in the measured temperatures of the wall for both greenhouses tend to get closer when temperature  $T_{ae}$  increases. They vary from 0.42 to 0.2 for SC and less than 0.08 for ST.

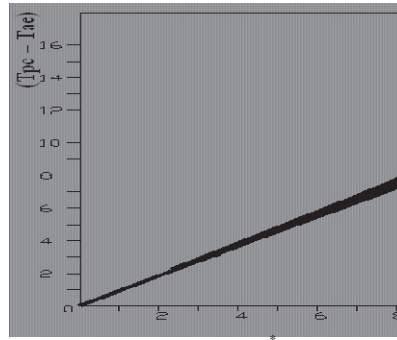


Fig. 6. Comparison between  $(T_{p_m} - T_{ae})$  and  $(T_{p_c} - T_{ae})$

The estimated temperature of the wall from the expression:

$$T_p = T_{pe} = T_{ae} + \frac{K(T_{ai} - T_{ae})}{h_{pe}} \quad (18)$$

The differences in the measured temperatures  $(T_{cf} - T_{pe})$  tend to increase as the wind speed goes from 0 m/s to 10 m/s. They vary between 0.2 and 0.7 °C for SC and are less than 0.12 °C for ST. Temperatures  $T_{pi}$  and  $T_{pe}$  measured on the wall in PE of the ST are extremely close, given the inertia of the material. The differences in the measured temperatures of the wall for both greenhouses tend to get closer when temperature  $T_{ae}$  increases. They vary from 0.42 to 0.2 for the chapel-shaped greenhouse and less than 0.08 for the tunnel-shaped greenhouse.

Which was derived from equations (10) and (13), is relatively correct, as the differences  $(T_{cf} - T_{pe})$  are very small. The estimate of  $T_p$  depends on the heat transfer coefficient (K) through the wall and on the surface exchange coefficients  $h_{pi}$  and  $h_{pe}$  that occur at the wall level.

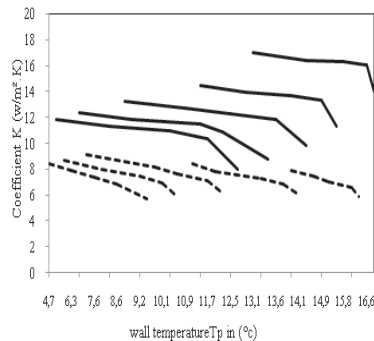


Fig. 7. Variation of coefficient (K) as a function of wall temperature  $T_p$

The sample of curves in Fig. 7 expresses the variation of the overall coefficient (K) of heat transfer through the wall as temperature  $T_p$  for both greenhouses varies. These curves confirm the nonlinearity of coefficient (K).

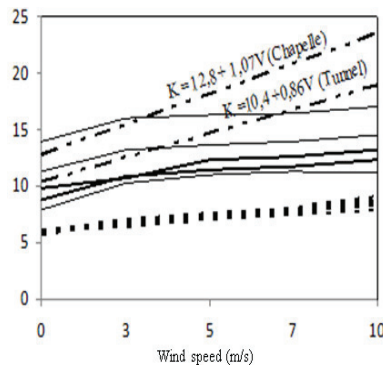


Fig.8. Variation of coefficient K as a function of wind speed for  $T_{ae} = 20$  °C.  $T_{ae}$  varies from 0 °C to 12 °C and  $f = 1$ .

This sample of curves in Fig. 08 expresses the variation of coefficient (K) as a function of wind speed from 0 m/s to 10 m/s. It appears that coefficient (K) tends to increase significantly as the wind speed goes from 0 m/s to 3m/s. This trend is less emphasized until the speed of 5 m/s. Coefficient (K) changes very little beyond that value.

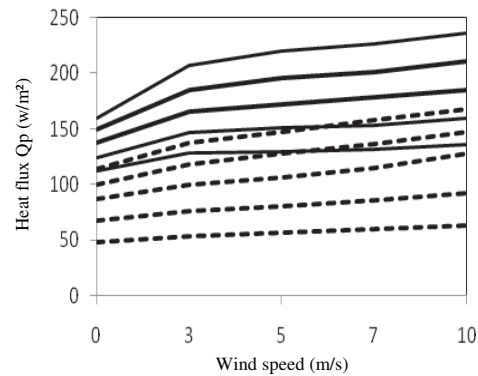


Fig.9. Curves of heat losses through the greenhouse wall as a function of wind speed, from 0 to 10 m/s;

The curves in Fig. 09 show heat losses through the wall of both greenhouses, as the wind speed rises up to 10 m/s and  $T_{ae}$  moves from 0 °C to 12 °C. It is well noted that these heat flows are relatively significant between  $v = 0$  m/s and  $v = 3$  m/s.

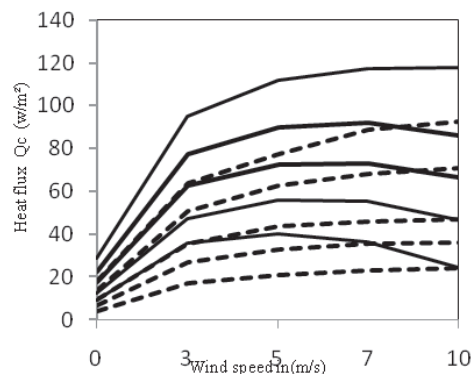


Fig.10. Curves of convection heat transfer through the greenhouse wall as a function of wind speed, from 0 to 10 m/s.

Convective heat loss curves are shown in fig. 10. Convective heat losses represent an important part in losses via heat flows through the wall of both SC and ST greenhouses. This illustrates the importance of the effects of wind and greenhouse ventilation on the behavior of the wall and the internal atmosphere

## 7. Conclusion

The work presented in this paper enables us to characterize the evolution of the overall heat transfer coefficient ( $K$ ) through the wall, according to the identification results, presented in Table 1. The samples of curves represent the evolution of coefficient ( $K$ ) as a function of the wind speed and the greenhouse wall temperature. They confirm the nonlinearity of coefficient ( $K$ ). The overall exchange coefficient, denoted by  $K = a + bv$  (Bailey et al, 1983), long used in our calculations, varies as a function of the wind speed and is a straight line. This line overestimates the values of coefficient ( $K$ ). This overestimation leads to a heat flow increase through the wall. Putting  $T_{pi} = T_{pe}$ , where  $T_{pi}$  and  $T_{pe}$  are the measured temperatures of the wall, the estimation of the wall temperature seems correct, as the differences ( $T_{ci} - T_{pe}$ ) are very small. This estimation enables us to better understand the radiative and convective surface exchanges at the wall. Convective losses, due to wind and greenhouse ventilation effects, are an important part in the overall losses of heat flows through the wall. This identification attempt represents a primary indicator only. Additional sophisticated identification works, extended to water balance, can further clarify the evolution of the overall heat transfer coefficient through the greenhouse wall and better characterize its behavior relatively to the radiative and convective surface exchanges phenomena that occur at the wall level.

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